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PLASMA RELAXATION

MICROWAVE PHYSICS LABORATORY, AFCRL

When radio energy is propagated through a plasma, part of the energy is absorbed by the plasma. This absorption of energy can lead to the plasma's modification. Just how such modifications come about is a nonlinear process of great complexity.

Absorption of electromagnetic energy by the plasma is another way of saying that the plasma particles are heated. An approach to understanding the heating mechanisms involves the study of the basic relaxation time--that is, the time it takes perturbed plasma to revert to its unperturbed state. Robert J. Papa of AFCRL has recently completed a study of the basic plasma-relaxation processes. He shows in this study that a very wide class of interactions of electromagnetic fields with plasmas may be described in terms of 10 basic relaxation times.

The three fundamental factors in all electromagnetic-field interactions with plasmas are: (1) the radio-wave period, or roughly, the reciprocal of the signal frequency; (2) the plasma oscillation period; and (3) the Larmor period, which concerns the motion of charged particles in magnetic fields.

Next, interparticle collisions must be considered. The electromagnetic field itself is coupled to the plasma through the process of interparticle collisions. This is the mechanism by which part of the electromagnetic-field energy is deposited into the medium. Continuing with the 10 factors described by Papa, the 3 relaxation times describing collision processes are: (4) the Maxwellianization time which relates to the self-interaction of electrons; (5) the momentum-relaxation time, which is the time it takes the drift velocity of the electrons to decay when the electromagnetic field is removed; and (6) the energy-relaxation time which is the time it takes for energy transfer between the different constituents comprising the plasma.

Now if we send a strong radio signal through the plasma, we then change the distribution in velocities of the electrons. This change in the density and spatial distribution of the electrons requires the consideration of three more relaxation times: (7) a total density-change relaxation time, and (8) a characteristic diffusion time. If ionization by electron impact on neutrals and attachment are significant processes, then it is important to consider (9) the rate of ionization and attachment.

Finally, if the plasma is exposed to the high-power electromagnetic field for only a finite length of time, then (10) an exposure time must be considered. This of course is

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important in cases where the electromagnetic field is pulsed.

Papa points out that seldom is it necessary, when studying electromagnetic-field interactions with plasmas, to consider all of the 10 factors. Furthermore, their effects vary in relative magnitude. Contrary to what might be expected from the standpoint of understanding plasma absorption mechanisms, a physical process associated with a particular relaxation time becomes more important when this relaxation time is smaller than the relaxation times of other competing processes. One of the most important single factors in the many processes of excitation and relaxation is that of electron temperature. The magnitude of some of the relaxation times can be greatly altered by raising or lowering the electron temperature. Altering the relative order of magnitude of the relaxation times can change the nature of the response of the plasma to a strong radio-frequency field.

The Papa study is important in that it classifies the types of nonlinear interactions of electromagnetic fields with plasmas. This classification gives the plasma physicist a clearer understanding of the exceedingly complex pattern of events that take place in a plasma during and immediately after the absorption of radio energy.

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OPTICAL PROPERTIES and ELECTRONIC STRUCTURE OF METALS

MAJOR JOSEPH P. MARTINO
Office of the Assistant Executive Director
AFOSR

The optical properties of metals have been studied for over a hundred years. Scientists of the early and mid-nineteenth century observed and measured the reflectivity of various metals, the absorption of various wave lengths of light by particular metals, and the transmission properties of thin films of metals. The development of a theoretical structure to explain the results, however, came later.

With the development of Maxwell's equations, which described light as electromagnetic waves, it became possible to describe in mathematical form the interaction of light with metallic conductors. Thus there evolved a theoretical framework which could predict certain optical properties of metals. Later, with the discovery of the electron, and the recognition that certain properties of metals are due to the ability of electrons to move about inside metallic conductors, the theoretical framework was further developed. Finally, with the elaboration of the quantum theory, the stage was set for a complete theoretical explanation of the optical properties of metals.

Unfortunately, the development of a theoretical explanation was hampered by the lack of reliable experimental data which could confirm or refute various plausible but untested theories. It has been only within the last decade that large amounts of reliable data have become available. Much of the data has not yet been fitted into a theoretical framework; nor has the existing framework been able to explain many apparent anomalies in the data.

In an attempt to bring together experimenters and theoreticians in the field of the optical properties of metals, an AFOSR-sponsored Symposium on Optical Properties and Electronic Structure of Metals and Alloys was held in Paris from 13-15 September 1965. The Symposium was attended by approximately 160 participants, with most of them coming from the United States, England and France, in that order. However, a total of 15 countries were represented, with some participants coming from Australia and Japan, as well as from most countries of Western Europe. Fifty-seven papers were presented, with the vast majority being reports of experimental results. Fourteen papers were given by AFOSR-supported scientists.

The Symposium was highly successful in bringing about an interaction among experimentalists, as well as between experimentalists and theoreticians. Many new and ingenious experimental techniques were reported, which had made possible the collection of data with a reliability not previously possible. The Symposium also provided renewed impetus to studies of the optical properties of metals and alloys.

The ability of optical measurements to provide information about the surface and bulk properties of metals and alloys is of particular significance to related fields of science, especially to programs of an applied nature. This is particularly true with regard to electronic structure, including the presence of impurities. Continued research in this field will lead to a better understanding of the nature and behavior of metals and alloys, and to better nondestructive testing techniques for analyzing metals and alloys.

Proceedings of the Symposium are available from the Interscience Publishers, New York City.

Micrometeorite Package on Gemini 9

Approximately three square inches of collecting surface were exposed for AFCRL on the recent Gemini 9 micrometeorite experiment. It was this micrometeorite package that was brought into the Gemini 9 capsule by Cernan during his space walk. The collecting surface was given to Dr. Robert K. Soberman and his group at the Space Physics Laboratory, AFCRL. Photo # 1 shows a hole in the bottom layer of a three-layered plastic film. This is an aluminum-coated nitrocellulose plastic film of 400 angstroms' thickness. In photo # 2 the dark spot is simply a flap of plastic created after the meteorite had passed through the film.

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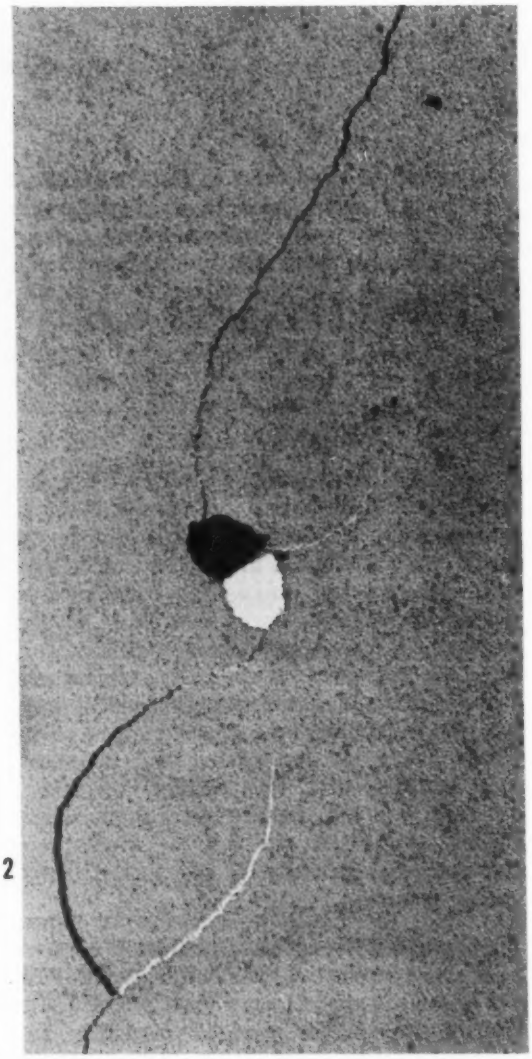

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ANNA AND PROGENY

OWEN W. WILLIAMS
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With the launch of the ANNA geodetic satellite in 1962, geodesists for the first time had an effective means for measuring distances between widely spaced locations on the earth's surface. AFCRL has been a major participant in the satellite geodetic programs that have taken place since then, including participation in the latest of these programs which centers around NASA's PAGEOS satellite launched in June 1966. With these satellites, distances are determined by triangulation methods from information obtained by photographing the satellite against a background of stars.

When distances to be measured are large--a thousand miles or so--satellites are ideal. But when we want to measure distances on the order of a hundred miles, we find ourselves in an awkward range where the distance is too short for satellite triangulation and too long for conventional ground surveys.

This has led AFCRL to test a new technique (or, more precisely, a new configuration of the satellite phototriangulation technique) for measuring shorter distances. In 2 separate tests carried out in June 1966 from AFCRL's Balloon Launch Facility at Holloman AFB, New Mexico, balloons with flashing strobe lights were sent to altitudes as high as 100,000 feet. The results of these tests indicate that the balloon-borne strobe-light technique will provide a means for accommodating this middle range. In the AFCRL tests, a 3-million-cubic-foot balloon was used to transport the flashing beacons. Three PC-1000 stellar cameras located in a triangle, with approximately 150-mile sides, photographed the flashing light against the stellar background for approximately 4 hours during each of the 2 tests. Exposures were taken simultaneously at the 3 stations every 15 minutes. Tracking of the strobe light at 100,000 feet presented no problem either with a theodolite or with field glasses. The time of each flash was recorded on a dual-channel tape recorder, with the National Bureau of Standards' Station WWV providing the real-time standard. Recovery of the lamp and its associated electronics package was made by parachute with a minimum of damage. Both were in working order upon recovery and were readied for flight within a few hours.

Preliminary examination of the data shows that a balloon-borne beacon can be a relatively inexpensive and effective tool for making geodetic surveys at intermediate ranges and in accessible areas. ★

ON THE GKD METHOD FOR THE LAMINAR BOUNDARY-LAYER EQUATIONS

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The laminar boundary-layer equations have largely defied exact solution. Consequently, the quest for approximate methods has been going on since the early 1920's. One of the approximate methods which seems to hold great promise is the Galerkin-Kantorovich-Dorodnitsyn N-parameter method of integral relations. The utilization of the GKD method for the solution of the laminar boundary-layer equations was recently studied in depth at the Hypersonic Research Laboratory (Ref. 1). The basic idea of this method, the historical background and some of the findings of this study are given in the following paragraphs.

The Method

The GKD method can be briefly summarized as follows: Let the given partial differential equation be denoted in operator notation as

$$F[u(x, y)] = 0 \qquad (1)$$

with suitable given boundary conditions on u (x, y). An approximate solution is taken in the form

$$u(x, y) \approx \tilde{u}_N(x, y) = \sum_{j=1}^{N} a_j(x)\, \phi_j(x, y) \tag{2}$$

where the assumed functions $\phi_j(x, y)$ satisfy the given y-boundary conditions for all values of the parameters $a_j(x)$. Further, the functions $\phi_j(x, y)$ are taken to be the first N members of a complete set of functions, that is, the $\phi_j(x, y)$'s are such that in the limit of large N, the approximating function $\tilde{u}_N(x, y)$, is equal to the function u(x, y):

$$\lim_{N \to \infty} \tilde{u}_N(x, y) = \lim_{N \to \infty} \sum_{j=1}^{N} a_j(x)\, \phi_j(x, y) = u(x, y) \tag{3}$$

The parameters $a_j(x)$ are determined by requiring that

$$\int_{y_1}^{y_2} H_j(y)\, F[\tilde{u}_N(x, y)]\, dy = 0; \quad j = 1, 2, \ldots, N \tag{4}$$

where the weighting functions, $H_j(y)$, are any set of linearly independent functions. The set of N linearly independent equations represented by equation (4) will be ordinary differential equations for the $a_j(x)$'s and will be nonlinear when the operator $F[u(x, y)]$ is nonlinear.

Background of the Method

The present method is an outgrowth of the work of B. G. Galerkin, L. V. Kantorovich and A. A. Dorodnitsyn. The earlier work was largely motivated by the approximate techniques developed by W. Ritz (1908, Ref. 2) to evaluate the form of a function, u (x, y), such that an integral, say $I[u(x, y)]$, was a minimum. Ritz assumed an approximating function of the form

$$u(x, y) \approx \tilde{u}_N(x, y) = \sum_{j=1}^{N} k_j\, \psi_j(x, y) \tag{5}$$

where the k_j's are constants. These constants are then determined to minimize the integral; that is, the constants k_j are determined from the condition

$$\frac{\partial I[\tilde{u}_N(x, y)]}{\partial k_j} = 0; \quad j = 1, 2, \ldots, N \tag{6}$$

Galerkin (1915, Ref. 3) divorced the method from the calculus of variations by noting that differential equations could be solved by assuming an approximating function of the form (5) and determining the constants from the equations

$$\int_{y_1}^{y_2} \int_{x_1}^{x_2} \psi_j(x, y)\, F[\tilde{u}_N(x, y)]\, dy dx = 0 \qquad j = 1, 2, \ldots, N \tag{7}$$

Kantorovich (1934 and 1942, Refs. 4 and 5) demonstrated that improved solutions could be obtained with the Ritz and Galerkin methods if the approximating function was taken of the form (2), viz.

$$u(x, y) \approx \tilde{u}_N(x, y) = \sum_{j=1}^{N} a_j(x)\, \phi_j(x, y) \tag{2}$$

The advantage of this procedure is that the function u (x, y) is explicitly approximated only in one independent variable; the behavior of the solution in the other variable is determined by the particular characteristics of the problem.

L. S. Leybenzon (1935) and V. V. Golubev (1936) constructed countably infinite systems of integral conditions from the laminar boundary-layer equations (Ch. 3 of Ref. 6).

However, these investigators made no attempt to solve the resulting systems of equations. A. A. Dorodnitsyn (1956, Ref. 7) applied the Kantorovich formulation of the generalized Galerkin method to solve the hypersonic blunt-body problem. In 1960 he published several solutions of Golubev's boundary-layer formulation after employing a simple, but significant, transformation of the dependent variable (Ref. 8).

Findings of Present Study

Several of the results found in Reference 1 are summarized in the following paragraphs. Since the objective of the study was to develop the computational technique and not to investigate solutions to specific problems, the incompressible laminar boundary-layer equations were considered. In this way the particularities of the method could be noted without having the results complicated by the necessary peripheral assumptions associated with compressibility, chemical effects, or turbulence. Also, the method could be directly compared with the exact and numerical solutions available for the incompressible laminar boundary-layer equations.

The practical consideration of how to formulate the approximate solution by the GKD method has been a barrier to the wide use of this method. Previous investigators formulated each order of approximation as a separate entity. The equations for each order were independently derived and programmed. This procedure is slow and tedious and limits the extension of the method to the first few orders of approximation. Consequently, an Nth-order solution technique was devised. With this technique a single equation is programmed which yields the necessary coefficients for the determination of the solution for any desired order of approximation. Solutions for the first 10 orders of approximation were obtained for several similar flows.

Although the set of weighting functions was originally taken as an arbitrary set of linearly independent functions, it was found that the accuracy of the GKD method depended upon the particular set chosen. In the investigation of this finding, the existence of classes of weighting functions was established. (A class of weighting functions is a group of sets of weighting functions which yield identical solutions when employed with the GKD method.) Then an optimum class of weighting functions was found. The optimum class is that which is composed of "sequentially complete" sets of weighting functions, that is, sets with

$$H_i(y) \sim y^{i-1} \qquad i = 1, 2, \ldots, N \tag{8}$$

Armed with an Nth-order solution technique and an optimum class of weighting functions, the exactness and convergence of the GKD method could be investigated in a meaningful manner. Since exact solutions exist for the similar flows, these were used as the basis for the investigation of the convergence of the method. The wall shear stress values as a function of the order of approximation for stagnation-point flow are given in Figure 1. Note that, although the first-order solution is 15 per cent in error, after the third order of approximation the error is less than 0.1 per cent and the solution converges uniformly.

The function which is represented by an approximate expression with N undetermined coefficients is the inverse of the velocity gradient $(\frac{du}{dy})^{-1} = \theta$. This inverse slope is inversely proportional to the shear stress

$$\theta \sim \tau^{-1} \tag{9}$$

and accordingly evidences a singularity as $u \rightarrow 1$ and, at the separation point, as $u \rightarrow 0$. Dorodnitysn utilized an approximating function of the form

$$\theta_N \sim (1 - u)^{-1} \tag{10}$$

which does not make provision for the singularity at the separation point; however, he was aware that, at the separation point

$$\theta \sim u^{-1/2} \tag{11}$$

Abbott (Ref. 9) first suggested an approximating function which would satisfactorily handle the separation point

$$\Theta_{N,a} \sim [(1 - u)\sqrt{a(x) + u}]^{-1} \qquad (12)$$

and Neilsen, et al. (Ref. 10) made computations with this form. In Reference 1 it was found that the approximating function of the form (12) could not be employed in the accelerated flow region. Consequently, for a flow which proceeds from a stagnation point to separation, the form (10) must be used in the accelerated flow region, and the form (12) in the retarded flow region. A procedure for changing from the form (10) to the form (12) was devised and tested for the external flow $U = 2 \sin (x/L)$. The resulting solutions are continuous within the accuracy of the method. These solutions for the first few orders of approximation are compared with the solution of Terrill in Table 1. The error in the fourth-order GKD solution is less than one per cent throughout the entire flow field.

In conclusion, the GKD method seems to hold its greatest possibility as a standard computation technique which can be readily applied to given external flow fields and will yield a solution in the fourth order of approximation which is in error by about one per cent or less. ★

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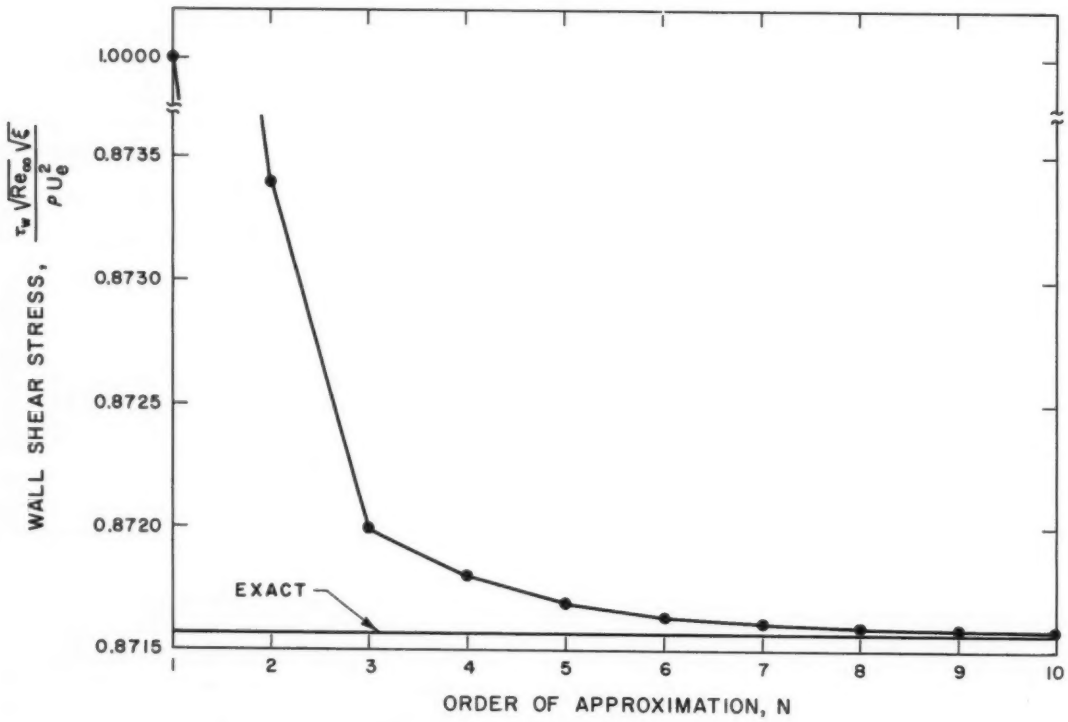

Figure 1. Wall Shear Stress Values for Stagnation Point Flow.

$\frac{x}{R}$	Terrill Ref. 11	GKD Method		
		Order of Approximation		
		4	3	2
x_s/R	1.823	1.82349	1.82322	1.81116
0.3	$\frac{\tau_w\sqrt{Re_\infty}}{\rho\, U_\infty^2\sqrt{8}} = 0.3569$	0.35674	0.35644	0.35723
	$\frac{\delta_1\sqrt{Re_\infty\sqrt{2}}}{R} = 0.6595$	0.65962	0.65870	0.65602
	$\frac{\delta_2\sqrt{Re_\infty\sqrt{2}}}{R} = 0.2971$	0.29685	0.29678	0.29946
0.5	0.5575	0.55730	0.55680	0.55806
	0.6813	0.68138	0.68042	0.67754
	0.3061	0.30582	0.30573	0.30850
0.8	0.7550	0.75471	0.75390	0.75570
	0.7408	0.74092	0.73984	0.73648
	0.3303	0.32991	0.32977	0.33276
1.0	0.7979	0.79760	0.79662	0.79868
	0.8057	0.80602	0.80481	0.80114
	0.3560	0.35548	0.35528	0.35848
1.2	0.7611	0.76076	0.75965	0.76228
	0.9031	0.90349	0.90208	0.89877
	0.3927	0.39220	0.39191	0.39538
1.5	0.5520	0.55169	0.55074	0.59122
	1.1685	1.16913	1.16790	1.17362
	0.4826	0.48202	0.48153	0.48616
1.6	0.4396	0.43908	0.43929	0.43003
	1.3241	1.32395	1.32354	1.41808
	0.5281	0.52733	0.52775	0.61683
1.8	0.1049	0.1058	0.10707	0.06621
	2.0326	2.02603	2.03807	2.10732
	0.6628	0.66192	0.66269	0.75269

Table 1. Approximate Solution of the Circular Cylinder Flow U = 2 sin (x/R).

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hypothesis by a Martian astronomer

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A Martian astronomer, looking at the earth through a telescope, might very well conclude that the earth is not entirely solid, but that a portion of it is a fluid in rotation relative to the solid portion. If he had to rely only on his telescopic observations of the motion of earth "spots," without the complementary observational and analytical techniques available to the earth-bound observer, he could cite strong evidence to support his hypothesis.

What would lead the Martian astronomer to his conclusion is the pattern of light and dark areas (earth spots) moving across the observable disk of the earth. The light areas that he should observe are associated with large cyclonic cloud systems. The dark areas are anticyclones where there is an absence of clouds and, hence, less reflected sunlight. By measuring the daily displacements of these bright and dark areas (assuming the solid earth is not visible), the observer would note that the earth would appear to rotate faster in the middle latitudes than near the equator.

The extraterrestrial observer would find that the earth spots have an average longitudinal motion of about 27 degrees during their usual lifetime of about 5 earth rotations. He would also observe that the bright spots would move poleward--about 2 degrees of latitude during their lifetime--while the dark spots would meander equatorward about 1 to 2 degrees.

While we on earth cannot, of course, observe these movements directly, we can nevertheless derive the information from surface weather maps quite easily. The observations just discussed were actually the result of a study of daily displacements, over a 2-year period, of all closed cyclonic and anticyclonic pressure centers appearing on northern-hemisphere surface weather maps. During the period of the study, 20,545 such centers were plotted at 1200 hours Greenwich time, and were analyzed.

The study was done by Norman J. Macdonald of AFCRL, and was undertaken to see if the gross circulation and mechanics of the earth's atmosphere could be deduced by measuring the daily displacements of the earth spots. Such a study of the motion of sunspots has led some solar physicists to

conclude that the mechanics of the solar atmosphere are similar, in the grossest sense, to those observed in the terrestrial atmosphere. Macdonald concludes that the sunspot-movement technique used to measure the solar circulation has some support from his measurements of the terrestrial atmosphere. The longitudinal and latitudinal motion of the earth and sunspots are correlated in such a way as to indicate the presence of an organized eddy structure in the motion of both atmospheres. ★

logical patterns in language

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In November 1962 the Directorate of Information Sciences, AFOSR, began partial sponsorship of the research of Dr. Herbert Bohnert at IBM's Thomas J. Watson Research Center, Yorktown Heights, N.Y. The work statement read, in part, as follows: "Establish logical structures implicit in portions of natural English and construct artificial languages whose rules permit an explicit statement of those structures in terms of symbolic logic." This sponsorship actually enabled Bohnert to continue his work, which he had begun several years earlier.

Dr. Bohnert's final report on Contract AF 49(638)-1198 is a clear summary of his work and reflects some of the effort that has been involved in fulfilling the above work statement. (1) The report has been so written as to be readable by linguists and logicians, as well as by persons in the computer sciences and those interested in philosophical language analysis. It contains, also, examples of fascinating foibles of language that may be discoverable only when computers are given the task of analyzing language structure.

Dr. Bohnert sought to demonstrate not only that logical formalisms could be used to systematize discussion about the structure of sentences, but that they could also be used to represent the deep structure of sentences. He started by designing a language he calls English I, whose grammar is essentially that of elementary logic itself, based on the thesis that the tasks performed by elementary logical notation represent, in fact, a linguistically based repertoire. He then proceeded to construct languages that were progressively more English-like by specifying exact definitions of sentencehood in terms of particular auxiliary concepts. The latest of the English-like languages that he considered in the report is called English II (previously called Logos IV). Computer programs are described that recognize the grammaticality of English-I and English-II sentences, and can translate English II to English I. The programs were written in the string-manipulating language SNOBOL 3. (Translation to logical symbolism, parenthesis or Polish notation, is a dictionary operation.)

Dr. Bohnert's report gives the results of his examination of the natural-language correlates of the logical concepts of degree, grouping, quantification, and scope. He has embodied in a single, machine-parse system several long-standing suggestions of logicians. Reichenbach, for example, suggested that the logical concept of predicate degree might be the basis for a unified understanding of the role of cases, prepositions, transitive-intransitive distinctions, active-passive relationships, and related phenomena. Amplification of the concept of degree led Bohnert to identify a concept he calls a "placer" which he characterizes as "a basic grammatical function category as yet little recognized by grammarians." It refers to words and phrases that function in a particular way in a particular context, for example, adverbially, though they may usually belong in another category. Bohnert's English I, like logic, has no compound subjects or predicates. It uses "not," "both," "either," and "if" like Polish groupers; however, this leads to clumsy, though unambiguous pile-ups of groupers. Bohnert devised a precedence system that assigns groupers to English II which, like natural

language, can have connectives unaccompanied by groupers. To avoid pile-ups, the precedence scheme has two connectives, "or else" and "and furthermore," that are weaker "or's" and "and's." The longer phrases that result are viewed as counterparts to pauses in the spoken language and the use of pause-like terms (e.g., "furthermore," "moreover") in the written language. Thus, for the phrase, "p and q and r or t," the new connectives enable direct distinction between (p . q) . (r v t) and p . ((q . r) v t).

Russell, Quine and others have commented that "any" in "any p" behaves logically like an unquantified variable restricted to the domain p. Bohnert has developed rules that make variations of quantifier scope a primary consideration in natural-language analysis. He notes that the translation of general terms into expressions involving quantifiers and variables "raises the question of the order of quantification in a way little suggested by traditional grammar itself." His scope rules, and a rule for quantifying according to a left-to-right order, give correct interpretations of the use of "any" and "every" in the context of a string, and of active-passive transformations when general terms rather than names are used. Thus, his program would find that "every boy likes no girl" is not the equivalent of "no girl is liked by every boy." English II includes dependent clauses introduced by the relative pronouns "who," "whom," and "which." Bohnert's present procedure would produce redundant clauses for the indefinite pronouns "something," "everybody," etc. Since English II does not contain third-person personal pronouns, it has less expressive power than English I and the predicate calculus. However, the exact class of formulas that English II can paraphrase has not been completely determined.

Natural-language factoring (e.g., "George runs or walks") can produce compounds that correspond to no traditional grammatical category (e.g., "George sent the card and Tom wired the bouquet to Joan"). Bohnert introduced the concept of "fragments" to handle factoring in general. A fragment is defined as an expression that would be a well-formed sentence if it were not defective in certain argument positions. Bohnert has added a further grammatical unit, the "apparent fragment," and a technique for grouping these into minimal distribution units. He discusses a calculus of "demand" computation that accounts for ways of combining and analyzing fragments; the term "demand" refers to values assigned to predicates by the dictionary. Bohnert anticipates that the calculus may be a valuable paradigm for analyzing a broad class of natural and artificial grammars. He also observes that it is not known whether a general rule could be given, even for a simple language, that would accommodate every possible unambiguous factorization. He sees further significance in abandonment of the sentence in favor of lists, tables, etc., when iterations grow very large.

Bohnert has shown that syntactic ambiguity need have little relation to semantic ambiguity for a machine if the machine's read-parse algorithm incorporates adequate resolution rules. (It should be noted that he considers the association of numbers, such as degree and precedence, with elements of vocabulary as syntactic information.) He observes that the embodiment of parsing algorithms in a computer program "is an almost indispensable heuristic procedure." Program runs repeatedly revealed subtle algorithmic errors that could not have been analyzed manually. The program runs also provided suggestions as to possible simplifying paraphrases. These results indicate that the logic of natural grammar is a fruitful area for theoretical linguistics. Of practical significance is the relevance of logic-based English-like languages to the design of artificial languages, to computer-assisted instruction programs, to information retrieval, to the development of machine inference techniques, and possibly even to progress in logic itself. ★

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vapor-solvent growth of semiconductors

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As modern technology imposes more and more stringent requirements on the physical characteristics of solid-state components, the science of material preparation faces an increasing number of new and difficult problems. The materials are often required in the form of single crystals. The problem is to grow such crystals with sufficient perfection of the lattice, with the specified level of purity, and in the most economical way. Among the several known methods of growing crystals (growth from the melt, growth from liquid solutions, growth from a sublimed vapor, etc.), a very old one has acquired increasing importance in recent years because of its often unique inherent advantages. This is the method known as vapor-solvent growth, or simply vapor growth. Basically, the method consists in inducing a solid substance to react, at a given elevated temperature T_1, with a gaseous agent (also called a solvent). The reaction products, which are also gaseous, are then led into another region of the apparatus that is maintained at a different temperature T_2 (T_2 could be lower or higher than T_1, depending on the characteristics of the reaction involved). At this temperature, the reaction products are less stable and the net result is that the original reaction now runs backward, thus precipitating the original material either on the container walls or on a suitably located seed. As an example, we may consider the chemical transport and growth of tungsten by means of the reaction originally studied by Langmuir and subsequently exploited by van Arkel, viz.:

$$W_{(solid)} + 3Cl_{2(gas)} = WCl_{6(gas)}.$$

In this case, tungsten (W) is the material that we wish to "transport" and eventually grow crystals of, chlorine (Cl_2) is the vapor solvent, and tungsten chloride (WCl_6) is the reaction product. The reaction is made to run from left to right at, say, 750°F, thus producing tungsten chloride. This is then led into contact with a tungsten seed kept at, say, 2500°F, where the reaction runs from right to left. Tungsten is therefore deposited onto the seed and the latter grows. We see, then, that superficially the process resembles that of sublimation or distillation. However, the material to be transported (tungsten in our example) has an extremely low vapor pressure, and could not be made to sublime at the operating temperatures. It is, instead, chemically transported. Thus, the vapor-solvent technique bears the same relationship to the growth technique from a sublimed vapor phase as the growth from liquid solutions to the growth from the melt.

Now what are the advantages, if any, of the vapor-solvent-growth technique with respect to others?* One advantage is that this technique allows us to grow crystals that are either difficult or impossible to grow by other means. This advantage is clear from the example that we have given above. Tungsten melts at temperatures higher than 6000°, and it is indeed difficult to grow crystals of it from the melt. In fact, this is also the case for other refractory metals (Mo, Ta). Presently, a variety of materials (GaP, SiC, B) are grown by means of the vapor-solvent technique, and more efficiently and more

*Before we consider the advantages, it may be fair to mention the major disadvantage of vapor growth, which is the sometimes unwanted inclusion of solvent atoms into the grown crystal. This is the second of two articles dealing with the preparation of single crystals for solid-state research. In the first article (OAR Research Review, Sept. 1966), we have seen that the vapor-phase method proved to be impractical for the growth of large single crystals of selenium -- an elemental semiconductor. The problem was solved by growing from the melt in a high-pressure apparatus.

conveniently than by other means. Another advantage of vapor growth is that it allows one to achieve impurity distributions in a given material, and therefore to make structures that are difficult to obtain by other means. This is particularly important in the semiconductor field for electronic components that must meet a number of specifications.

Perhaps the most illuminating example of the importance of vapor growth is found in silicon transistor technology. It may be worthwhile, therefore, to devote some attention to this problem. For the sake of simplicity, let us consider only one type of device, the N-P-N transistor. This terminology means that one portion of the crystal (called the emitter) exhibits N-type conductivity, the adjacent portion (called the base) has P-type conductivity, and the rest of the crystal (called the collector) has again N-type conductivity.

We can make a silicon crystal an N-type conductor by doping it with phosphorus, i.e., by diffusing phosphorus into it. Phosphorus has more valence electrons than silicon, and therefore its introduction into the silicon lattice makes electrons available for the conduction of electricity. Since electrons have a negative charge, one speaks in this case of N-type conductivity (N for negative). The higher the doping level (i.e., the more phosphorus we diffuse into the silicon), the higher the conductivity.

P-type conductivity, on the other hand, can be achieved by doping with boron. This element has less valence electrons than silicon; therefore, its incorporation into the lattice gives rise to a deficiency of electrons and the current is carried by electron holes (positively charged, hence P-type). In an N-P-N silicon transistor, the emitter is very heavily doped with phosphorus, and the base is moderately doped with boron. Doping, as we said above, can be achieved easily by diffusion, which is a good inexpensive method of achieving desired impurity configurations and is well adapted to oxide masking. The problem that arises in the N-P-N transistor is this: what should be the doping level of the collector for best operation of the device?

Suppose, at first, that the collector is only lightly doped (with, say, about 1 ppm of phosphorus), as indicated schematically in Fig. 1a. Since, for optimum performance of the transistor, the base-collector junction should be reverse-biased with about 10 volts, light doping would be good. It would be desirable also because it would make the junction capacitance C low, as desired for high-speed operation. But the conductivity of the bulk collector region would also be low; i.e., the electrical resistance R would be high. This would be undesirable because high resistance means high Joule's heat (I^2R) loss and also slow speed of switching due to high RC. So we see that light collector-doping would give favorable junction characteristics but unfavorable bulk properties. If, on the other hand, we were to dope the collector heavily (with, say, 100 ppm of phosphorus), as depicted schematically in Fig. 1b, the reverse would be true. We would get low bulk-resistance R (and hence small I^2R losses and low RC values); but we would also get high junction-capacitance C and low breakdown-voltage at the junction, which could not then withstand the 10 volts desired for optimum performance. The requirements are obviously conflicting. The problem can be solved only by heavily doping (~100 ppm) the bulk of the collector region and lightly doping (~1 ppm) the interface layer of the collector, as shown schematically in Fig. 1c. The

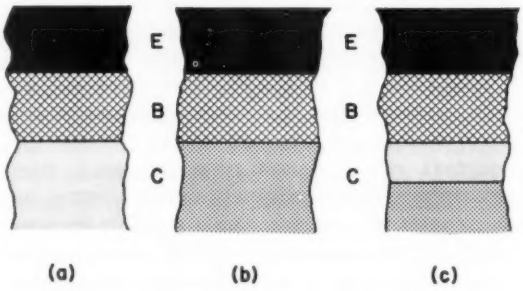

Fig. 1. Schematic representation of the emitter-base-collector region in an N-P-N transistor. E = emitter, very heavily doped, N-type. B = base, heavily doped, P-type. C = collector, N-type, lightly doped in (a), heavily doped in (b), optimized for best performance in (c).

former makes the collector-resistance low, and thus reduces the time required to charge up the capacitance of the base-collector junction. It also reduces resistive heating effects so that devices can be packed closer together. The latter optimizes the properties of the junction by allowing it to sustain an appreciable reverse bias, and by providing for a low junction-capacitance.

This collector configuration cannot be achieved by diffusion, however, because the diffusion process yields a highly non-uniform distribution of dopant which is obviously undesirable in this case. At present, the only way to achieve this configuration economically is to employ the vapor-solvent technique. One starts with a single crystal of silicon that has been grown from the melt with a high concentration of phosphorus, i.e., a heavily doped crystal. This crystal is cut into thin wafers (about 5 thousandths of an inch thick) which are then suitably lapped and polished. Then, by a vapor-solvent technique discussed below, a very thin layer of lightly doped silicon is grown epitaxially onto the surface of each wafer. This layer is only about 0.1 or 0.2 thousandths of an inch thick. It is into this thin layer that one then diffuses the base and emitter regions. Figure 2 shows a schematic cross section (approximately to scale) of the actual transistor. Note that the vapor-grown layer allows one to achieve the planar configuration, as the actual collector contact is also diffused into this layer approximately one thousandth of an inch away from the emitter region.

One might say that almost all silicon transistors used today are manufactured in the way outlined above. This fact alone is sufficient to emphasize the importance of vapor-solvent growth in modern technology. It is because of this importance that F. Jona and R. F. Lever, at the IBM Research Center, have undertaken a series of fundamental studies of the vapor-growth process (2-7) under AFOSR sponsorship. We shall discuss here some of the results obtained from their investigations.

The actual process for vapor growing a thin layer of silicon onto a silicon seed was developed by Theuerer (1) at the Bell Telephone Laboratories. It involves passing a gaseous mixture of silicon tetrachloride ($SiCl_4$) and hydrogen (H_2) over a hot silicon seed. The presence of hydrogen is necessary because the silicon-tetrachloride molecules would not decompose by themselves, even at the fairly high temperature of the seed (about 2000°F). What the hydrogen does is to chemically reduce the chloride on the hot seed surface, thus producing gaseous HCl and depositing Si onto the seed. The chemical reaction may be summarized as follows:

$$SiCl_{4(gas)} + 2H_{2(gas)} = Si_{(solid)} + 4HCl_{(gas)}.$$

It will be clear to any chemist that the system actually must be much more complicated than that. Doping is achieved during growth by introducing into the gas stream suitable concentrations of phosphine, which is a source for the phosphorus needed to attain the required conductivity.

Normally, one would like to accelerate the growth process, for obvious economical reasons. It is found, however, that if one tries

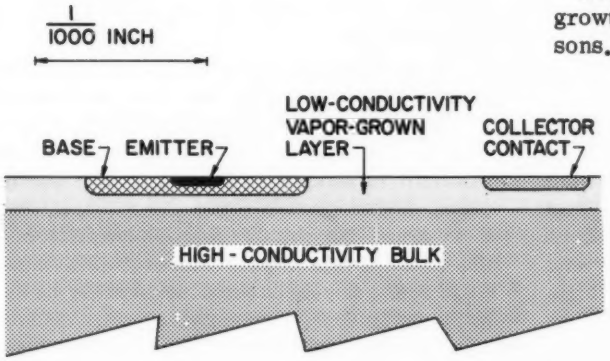

Fig. 2.

Cross section through silicon planar transistor (approximately to scale). Note that the bulk has been cut in the drawing, but does in actual fact have a thickness of 0.005 inch.

to get more Si down on the seed by increasing the temperature, the efficiency of the reaction increases rapidly at first up to about 2000°F, but then remains roughly constant even if the temperature is raised up to the melting point of silicon. If, on the other hand, one tries to keep the temperature constant at, say, 2000°F, and if one increases the concentration of $SiCl_4$ within the H_2 stream (i.e., the ratio of chlorine to hydrogen in the gas), one finds that the rate of Si deposition increases to a maximum, but then decreases and finally becomes negative. This would mean that the seed eventually etches instead of growing.

A study by Lever (4) showed that these experimental facts can be understood by means of chemical-equilibrium considerations. These equilibrium studies are complicated because there are at least nine gaseous species that are known to exist in the gas phase of the system, namely $SiCl_4$, $SiHCl_3$, SiH_2Cl_2, SiH_3Cl, SiH_4, $SiCl_2$, SiCl, HCl, and H_2. Thermodynamic data on all these species have become available in recent years in National Bureau of Standards and Bureau of Mines bulletins as well as in Joint Army-Navy-Air Force tables.

The problem was to find a suitable parameter with which one could characterize the gas phase and which could be used to provide a good criterion for the efficiency of the reaction. Such a parameter was found to be the silicon-to-chlorine ratio in the gas phase in terms of these independent variables: pressure P, temperature T, and chlorine-to-hydrogen ratio in the gas phase. The main result of the study is contained in Fig. 3, which is a map displaying the chlorine-to-hydrogen ratio as a function of temperature, the contour lines being lines of constant value of the silicon-to-chlorine ratio. It is clear from this plot that, for a given value of the chlorine-to-hydrogen ratio between, say, 10^{-2} and 10^{-1}, the ratio of silicon to chlorine varies very little above 1400°K (≈ 2000°F). This is due to the fact that, in this temperature range, the species $SiCl_2$ becomes increasingly important, and it explains the fact that the reaction efficiency remains practically constant. If, on the other hand, one keeps the temperature constant (at, say, 1400°K in Fig. 3), and one increases the chlorine-to-hydrogen ratio in the gas stream, one sees from the map that one ultimately will cross the shaded contour line that corresponds to a silicon-to-chlorine ratio of 0.25, which is the value corresponding to $SiCl_4$. Above this line, the actual value of the silicon-to-chlorine ratio in the gas phase increases above the ratio 0.25, which can only happen if silicon goes into the gas phase from the seed. Hence we understand the etching of the seed that is observed experimentally under the conditions described.

As illustrated above in the discussion of transistors, doping is a very important process. Particularly important is the growth of suitably doped materials by the vapor-solvent technique. The silicon-hydrogen-chlorine system discussed above was considered much too complex, however, for providing the necessary understanding of the basic phenomena involved. A simpler system, the germanium-gallium-iodine system (where iodine is the vapor solvent, germanium the material to be grown, and gallium the dopant), was therefore chosen. Germanium crystals heavily doped with gallium are useful for the manufacture of tunnel diodes.

One encounters a problem when trying to vapor-grow heavily doped epitaxial layers of germanium. One generally uses as a source material polycrystalline germanium that already contains high concentrations of gallium (say, 0.1%). If one uses iodine as a vapor solvent (convenient because it permits the growth of epitaxial germanium layers at quite low temperatures), one finds that the grown material contains hardly any gallium at all.

Extrapolating the knowledge acquired in the growth from the melt, one may be tempted to say, at first, that this is simply a case of low distribution coefficient, and that the problem is simply to determine this coefficient. In the growth from the melt, in fact, it is found that the distribution coefficient--the ratio of the dopant concentration in the solid to the dopant concentration in the melt--is approximately constant. Hence the required doping level in the solid is achieved simply

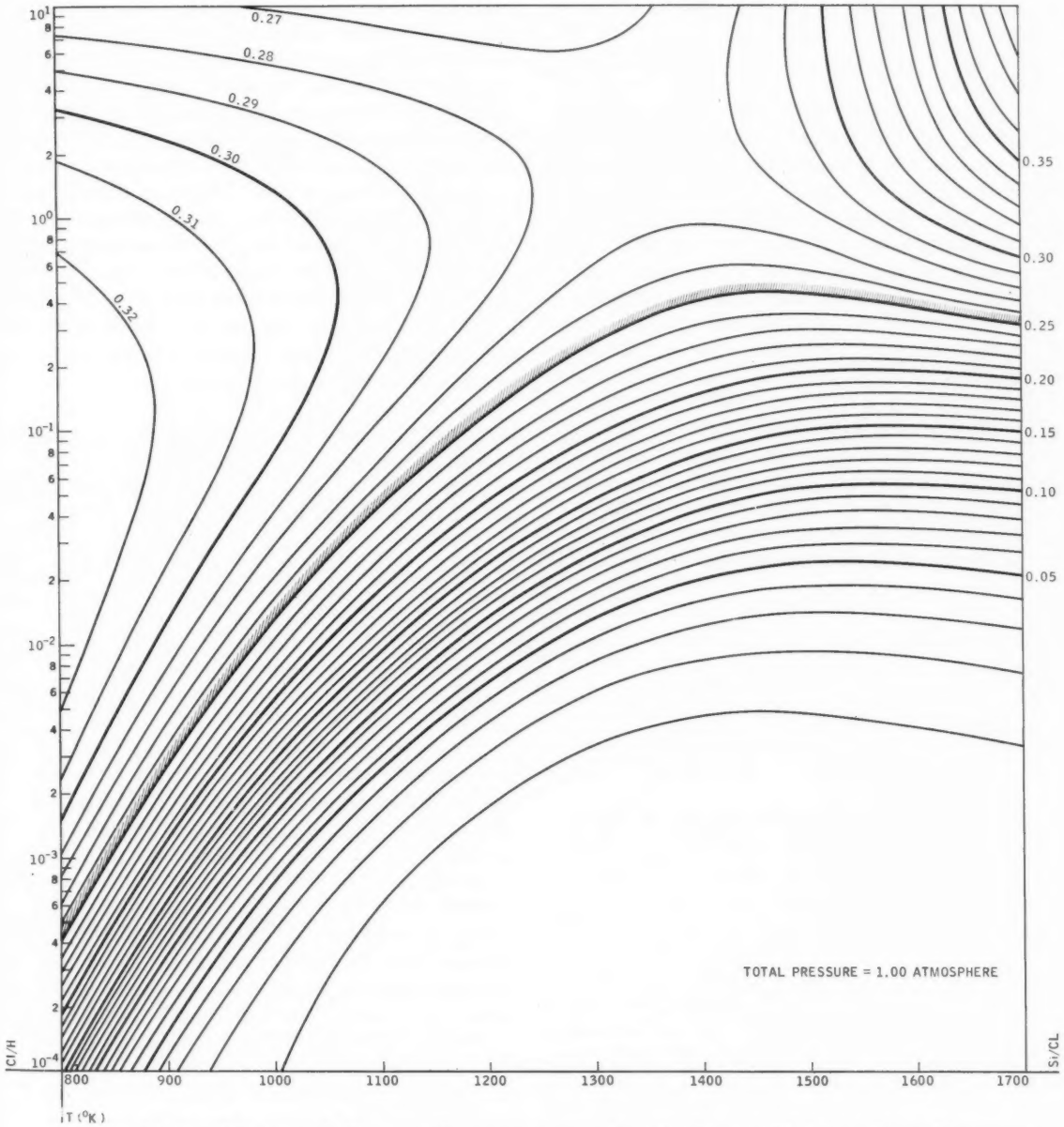

Fig. 3. Plot of chlorine-to-hydrogen ratio versus temperature (in degrees K). The contour lines represent constant values of the silicon-to-chlorine ratio. The total pressure is one atmosphere.

by adding the appropriate amount of dopant to the melt. It turns out, however, that the doping problem in vapor growth is different and more complex than in melt growth, since it involves both the thermodynamics of solid solutions and the thermodynamics of gas-phase mixtures. In fact, no treatment of the problem existed in the literature before the analysis of the Ge-Ga-I system discussed here. (6) This analysis was made by considering thermodynamic equilibrium and gaseous diffusion, and was confirmed experi-

mentally by showing that it predicts correctly the concentration and growth rate of heavily gallium-doped germanium by iodide vapor transport.

One of the results of this study is shown in Fig. 4, which depicts the mole fraction of the species present in the gas phase as a function of the total pressure of the gas in the system at a temperature of about 900°F. The gas phase is in equilibrium with solid germanium containing about 25 ppm of gallium. The figure shows, then, that at pressures close to one atmosphere, the gas phase consists preponderantly of gallium-bearing species. This is due to the fact that gallium has great affinity for iodine and goes into the gas phase in the form of iodides. Consequently, the gallium atoms will tend to remain in the gas phase bound to iodine atoms, leaving only little gallium available for incorporation into the solid. Another consequence of the above fact is that little iodine

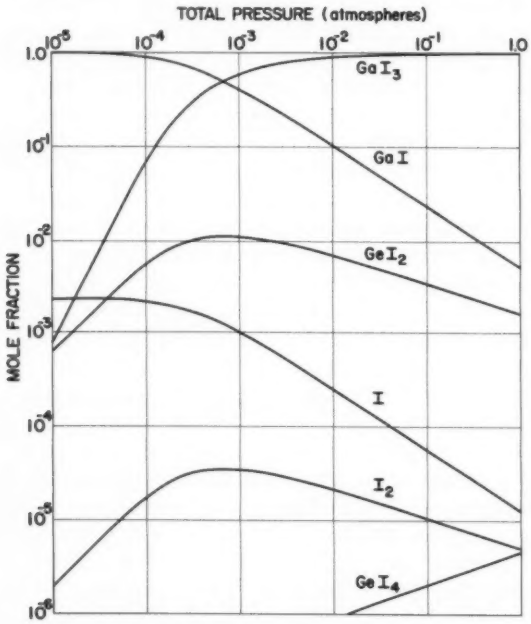

Fig. 4. Mole fractions of the various species present in the gas phase in the Ge-Ga-I system versus total pressure in atmospheres. The gas phase is in equilibrium with solid germanium containing about 25 ppm of gallium at 900°F.

will remain available for the transport of germanium. In other words, the gallium "crowds out" the germanium. One conclusion, then, is that in order to vapor-grow heavily gallium-doped germanium, one must add an appropriate excess of gallium iodides to compensate for the portion that must remain in the gas phase under equilibrium conditions. Another conclusion is that growth at low temperatures would be impractically slow. The analysis allows one to choose the appropriate independent parameters for the successful growth of heavily doped germanium. Experiments confirm the theoretical predictions in a satisfactory way.

Another aspect of vapor growth that was considered in the AFOSR-sponsored research discussed here is the more fundamental one of what is going on in the gas phase and at the surface of the growing crystal. Growth is obviously the result of at least two processes operating in series: (A) vapor transport and (B) surface reactions. Process (A) literally involves the transport of gas molecules from a given point (which could, of course, be the source) to the seed location. The gas phase, as we have seen in our discussion above, is often quite complex, in the sense that it involves a large number of species originating often from several chemical reactions. Calculations of the composition of the gas phase at the source location are usually made under the simplifying assumption that chemical equilibrium obtains between source and gas phase. This naturally requires that the pertinent thermodynamic data be determined. (3) At the more common operating pressures of closed systems, the actual transport of the gas phase to the seed location involves mostly diffusion (7, 2), although sometimes convective effects can play very important roles. (2) Once the gas molecules land on the surface of the seed, the actual process of reaction begins. This depends not only on the actual composition of the gas phase in contact with the seed surface, but also on the chemical, physical and crystallographic nature of the seed surface. It is clear, therefore, that the two processes, (A) and (B), represent only extreme cases. In some cases, the growth process may be controlled preponderantly

by gas diffusion (one speaks, then, of diffusion-limited growth); in other cases, it may be controlled mostly by what happens at the growing surface (surface-limited growth). In most cases, however, both limitations interact to a certain extent. (5) The nature and extent of this interaction have been elucidated. (7) Actually, the interrelations are fairly simple. If we call J_S the growth rate in the surface-limited case, and J_D the growth rate in the diffusion-limited case, then the actual growth rate J attained is given by the equation

$$\frac{1}{J} = \frac{1}{J_S} + \frac{1}{J_D} .$$

We can conclude, therefore, that we have achieved sufficient fundamental understanding of the vapor-transport process and the way it interacts with the surface-reaction process to proceed to the next phase of the inquiry. This is concerned with the surface of the solid and what, in detail, goes on over it. This phase, already in progress in several laboratories, will require a more quantitative understanding of the nature and behavior of solid surfaces than we have at present. (8) ★

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SCIENTIFIC NOTES

Surveyor Data Verifies AFCRL Studies: Measurements of infrared and X-ray emissions from the moon, the analysis of the effects of meteoric bombardment, of radiation, and of extreme temperature changes, and the actual study of pulverized silicates under high-vacuum conditions, all pointed to the existence of a hard, firm lunar surface. Most lunar geologists, including AFCRL scientists who over the past several years conducted the range of studies noted above, predicted this. But there was nevertheless always an element of uncertainty until the Surveyor I provided in situ evidence. (Space Physics Laboratory)

Construction of Vacuum Telescope Begins: Construction has begun on AFCRL's 328-foot solar vacuum telescope at AFCRL's solar observatory on Sacramento Peak, N.M. Because 200 feet of the over-all length will be beneath the ground, the first step in the construction is the excavation of a mammoth hole in the ground. The hole has now reached an impressive depth. Completion of the telescope is scheduled for July 1968. (Space Physics Laboratory)

Rocket Measures EUV Radiation: AFCRL launched an Aerobee-150 sounding rocket from the White Sands Missile Range, N.M., last July 19th in an experiment to measure solar radiation in the extreme-ultraviolet (EUV) region. The rocket carried a 195-pound payload to an altitude of 148 miles. Measurements were made between 1,300 and 250 angstroms in the extreme ultraviolet using a grazing incidence photoelectric monochromator installed in the Aerobee nose cone. The instrument was equipped with a biaxial pointing control device which locked on the sun as measurements were made. Another experiment on board employed a retarding potential analyzer for measuring ion and electron densities at that altitude. Data was telemetered to ground receiving stations. James E. Higgins is the AFCRL project scientist. (Upper Atmosphere Physics Laboratory)

SATELLITE ATTITUDE-SENSING SYSTEM BASED ON POSITIVE-ION DETECTION

UPPER ATMOSPHERE PHYSICS LABORATORY, AFCRL

Space vehicles in orbit about the earth move through a continuous stream of charged particles. This flow of charged particles can be detected by sensors. Sensitivity of the detection system varies with the orientation of the sensors with respect to the direction of motion of the spacecraft. With this as a basis, it is possible to design a system that can sense and control the attitude--the pitch and the yaw--of the spacecraft.

Such a system has been designed and fabricated at AFCRL and provided to the McDonnell Aircraft Company for installation in the Gemini 10 (launched July 18th) and Gemini 12 spacecraft (to be launched in November). NASA has given the AFCRL experiment the designation, D-10. The system was designed by Rita Sagalyn and her group at AFCRL who, through scores of rocket and satellite experiments over the past decade, have made major contributions to the understanding of ion and electron densities and their variations in the upper atmosphere.

Two sensor systems--one to detect pitch, the other to detect yaw--were designed for both the Gemini 10 and 12. Each sensor is located on a boom extending out about 3 feet from the spacecraft. The 2 booms are separated by about 90 degrees near the midsection of the Gemini capsule.

The attitude-sensing experiment was conducted aboard the Gemini 10--and will also be conducted aboard the Gemini 12--in a near-circular orbit at an altitude of about 160 nautical miles, within the ionosphere's F-region. Typical charged-particle densities in this region vary from 10^4 per cubic centimeter at night to 10^7 particles during the day. (Neutral particles in this region have a density of about 10^{10} per cubic centimeter.)

Although we can assume an equal distribution of electrons and ions within the orbit of the spacecraft, the AFCRL sensor is designed to detect only ions. Relative to the high, randomly oriented electron velocities, which are 200 times greater than the slower-moving ions, the spacecraft is essentially stationary. The spacecraft, however, has a velocity 8 times that of the random thermal velocity of ions. Thus, spacecraft velocity and direction relative to the ion environment can be detected.

In measuring spacecraft attitude, what we want to know is the angular variation of a reference axis to a velocity vector. Now, if we place a conducting ring perpendicular to the velocity vector of the spacecraft, and screen out the flow of electrons, the flow of positive ions will produce a current in the ring. The current will decrease in an analytically predictable manner as we rotate the ring from the maximum current-flow position, which is perpendicular to the velocity vector. But this arrangement of a single ring could not tell us much about the spacecraft attitude.

A second ring on a plane 90 degrees from the first is needed. Now, if we place the 2-ring system so that each ring is 45 degrees from the pitch reference axis of the spacecraft, the flow of current from each should be equal when the reference axis is aligned to the velocity vector. When the reference axis is not aligned, the current flow in each of the 2 rings will be different, and this difference can become a measure of the spacecraft's pitch angle. To measure yaw it is necessary to install another system, similar in all respects, aligned about the spacecraft's yaw axis.

The actual system developed by AFCRL for Gemini 10 and 12 is more complex than

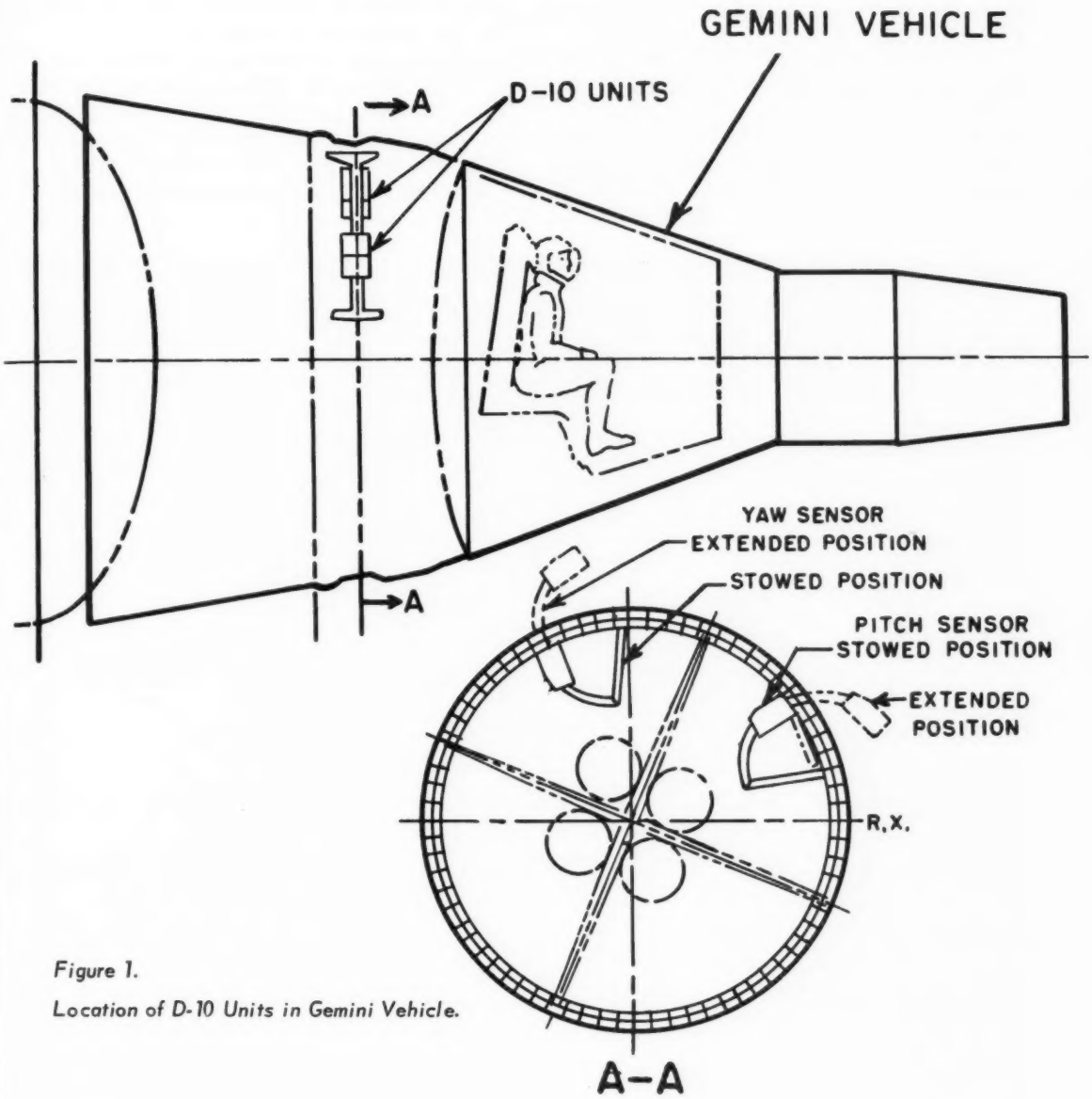

Figure 1.

Location of D-10 Units in Gemini Vehicle.

this, with much of the complexity centering around methods for electrically biasing the system to reject electrons, enhance ion collection, and reduce the emittances from grids and collectors. The sensors must be located on extendible booms in order to minimize spacecraft shadowing and the charge that builds up on the spacecraft, which might interfere with the detector system.

The electronics system, consisting of precisely balanced addition, subtraction, and ratio circuits, is mounted on 5 printed circuit boards which, in turn, can be fitted into

a small aluminum container measuring about 4 by 6 by 8 inches.

The attitude-control system carried aboard the Gemini 10 and 12 vehicles is an experimental system and is not a part of the Gemini primary control system itself. The astronauts aboard the Gemini vehicles are simply testing its potential effectiveness for future operational systems. As an operational system, it would be particularly suited to docking and maneuvering in space.

The Gemini 10 astronauts devoted more time to testing the attitude-sensing system than to any other of the 15 experiments carried aboard. The 16-pound AFCRL system was found to be more accurate than the Gemini 10's 150-pound operational gyro system. ★

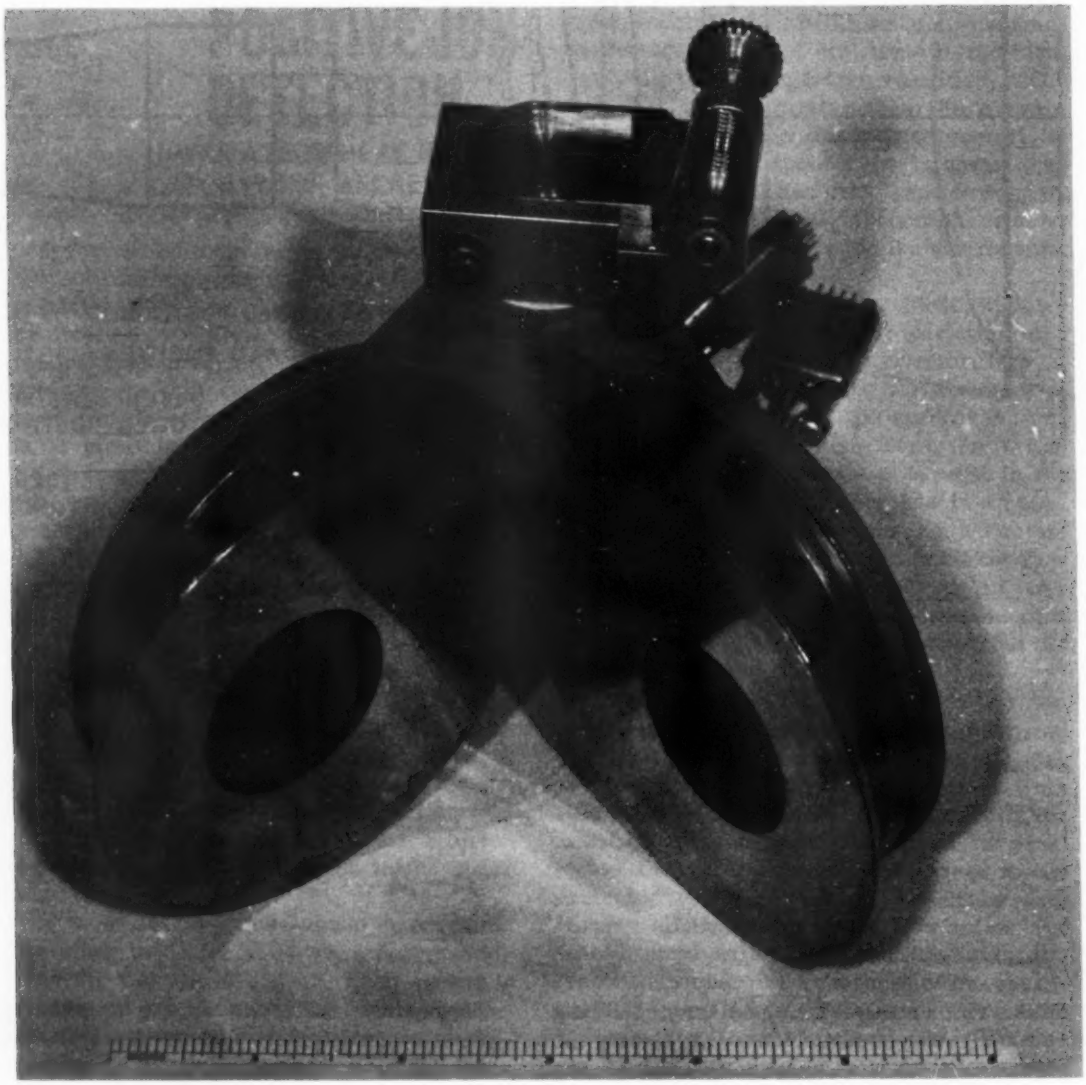

Photo #1. This shows the two rings through which the positive ions pass, creating a current. Two of these systems, exposed on the end of an extendible boom, were used on the Gemini 10. The same equipments will also be used on Gemini 12. One such system is used for pitch, the other for yaw.

AN INVESTIGATION OF THE BEHAVIOR OF A DETONATION WAVE IN A FLOWING COMBUSTIBLE MIXTURE

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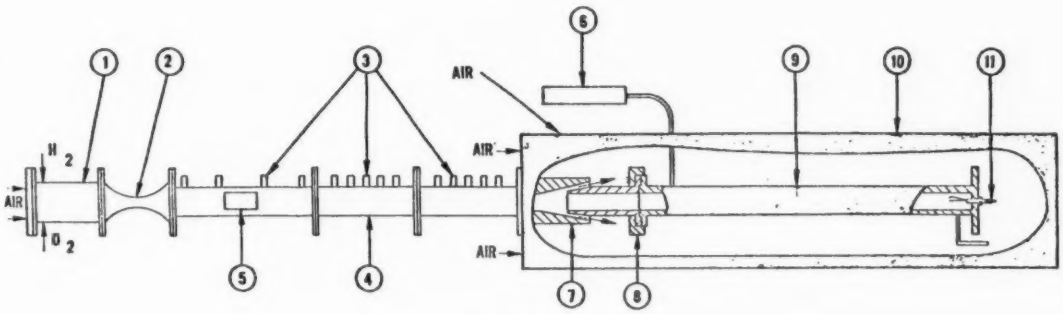
Air Force Institute of Technology

The study of detonation waves that propagate in a flowing combustible mixture is of great interest today because of the occurrence of such waves in some combustors. Studies have indicated that undesirable combustion instability in rocket motors has characteristics of detonation. Also, it may be possible that some type of a detonation process could be used in supersonic combustion. In both of these areas, the detonation wave would be in an environment of flowing gas (subsonic in the former and supersonic in the latter). Studies in the past have been concerned primarily with the detonation wave propagating into a static mixture.

This research included a theoretical study of detonation parameters for various initial conditions that corresponded to those encountered in the flowing gas. It was expected that the detonation-wave velocity relative to the unburned gas should be independent of the speed of the flowing gas, and the profile of the wave should be altered from a planar front to a shape similar to the velocity profile of the oncoming flowing gas.

A stoichiometric mixture of hydrogen and oxygen gas was used. Flow velocities were varied throughout the subsonic range, and flows from Mach 2, 3, and 4 nozzles were

Lt. Col. McKenna performed this research under the auspices of the Fluid Dynamics Facilities Research Laboratory, ARL, in partial fulfillment of the Ohio State University requirements for the Ph.D. degree.



LEGEND

1. Stagnation Chamber
2. Nozzle
3. Ionization Probes
4. Flowing Gas Detonation Tube (FDT)
5. Viewing Section
6. Mixing Chamber
7. Transition Section
8. Diaphragm Assembly
9. Initiation Detonation Tube
10. Exhaust Duct
11. Ignition Assembly

Figure 1. Schematic Diagram of the Detonation System.

studied in the supersonic range. The apparatus consisted mainly of a stagnation chamber, a flowing gas detonation tube, and a convergent-divergent nozzle (when supersonic). The detonation wave was initiated in a static mixture in a separate tube downstream of the main tube. After initiation, the wave propagated upstream (ruptured a diaphragm at the end of the initiation tube) into the oncoming flowing combustible mixture of gas. Measurements were made of the relative velocity of the wave by means of ionization probes that fed signals to an oscilloscope with a raster modification. Schlieren photography was used to obtain pictures of the wave as it propagated against the flowing gas.

Analysis of the data indicated that the detonation wave did behave as was expected for the subsonic flows, but not for the supersonic flows. The data indicated that the absolute wave velocity was greater than the absolute Chapman-Jouguet steady velocity. Thus, the wave exhibited characteristics of a strong detonation wave. This increase in speed was attributed to the particular pressure environment behind the wave that was present in the supersonic flow. Also, it is possible that the wave was strengthened by explosions behind the wave that resulted in detonation waves that were observed in two of the Schlieren photographs. The Schlieren photographs revealed little change in the planar front of the wave in the subsonic flow; but there was a definite curvature of the front that corresponded to the velocity profile of the oncoming gas in the supersonic flow. The photographs revealed very clearly the propagation of the detonation wave into the boundary layer. This condition resulted in disturbances appearing ahead of the wave in the photograph--but was obviously explainable in that the wave and flow were three-dimensional.

The experimental part of the study encountered the problem of accidental detonation of the flowing hydrogen-oxygen gas. Without normal ignition, the gas would detonate during the time when the flowing gas was permitted to enter the tube and when it reached a steady-flow condition. This accidental detonation occurred randomly. A few times it occurred even at low subsonic velocities, but more frequently at supersonic velocities. Although this phenomenon was thoroughly investigated, it was not possible to determine the cause of these unwanted ignitions. Therefore, automatic shutdown devices were used to avoid damage to the equipment. ★

properties of materials in solid-state form

SOLID STATE SCIENCES LABORATORY, AFCRL

Why do certain combinations of atoms in a particular crystal lattice result in a material with distinctive and unique properties? Is it possible to predict in advance of the synthesis of the material what its properties will be? In research extending over a period of 10 years, Dr. Johannes N. Plendl of AFCRL has sought answers to these fundamental questions. This research has uncovered many unsuspected relationships among the properties of solid materials--and has given the solid-state physicist a key to the theoretical prediction of the properties of a given material.

We can characterize the properties of solid materials in many different ways--by valence, bond strength, elasticity and compressibility, specific heat, lattice cohesive energy, hardness, infrared spectrum, and so on. What are the relationships among these methods of characterization? If we know the infrared spectrum of the material, for example, can we derive its compressibility or hardness? The apparent absence of such relationships has been a concern to physicists for many decades. Dr. Plendl has provided new insights into these relationships which, until now, have defied basic

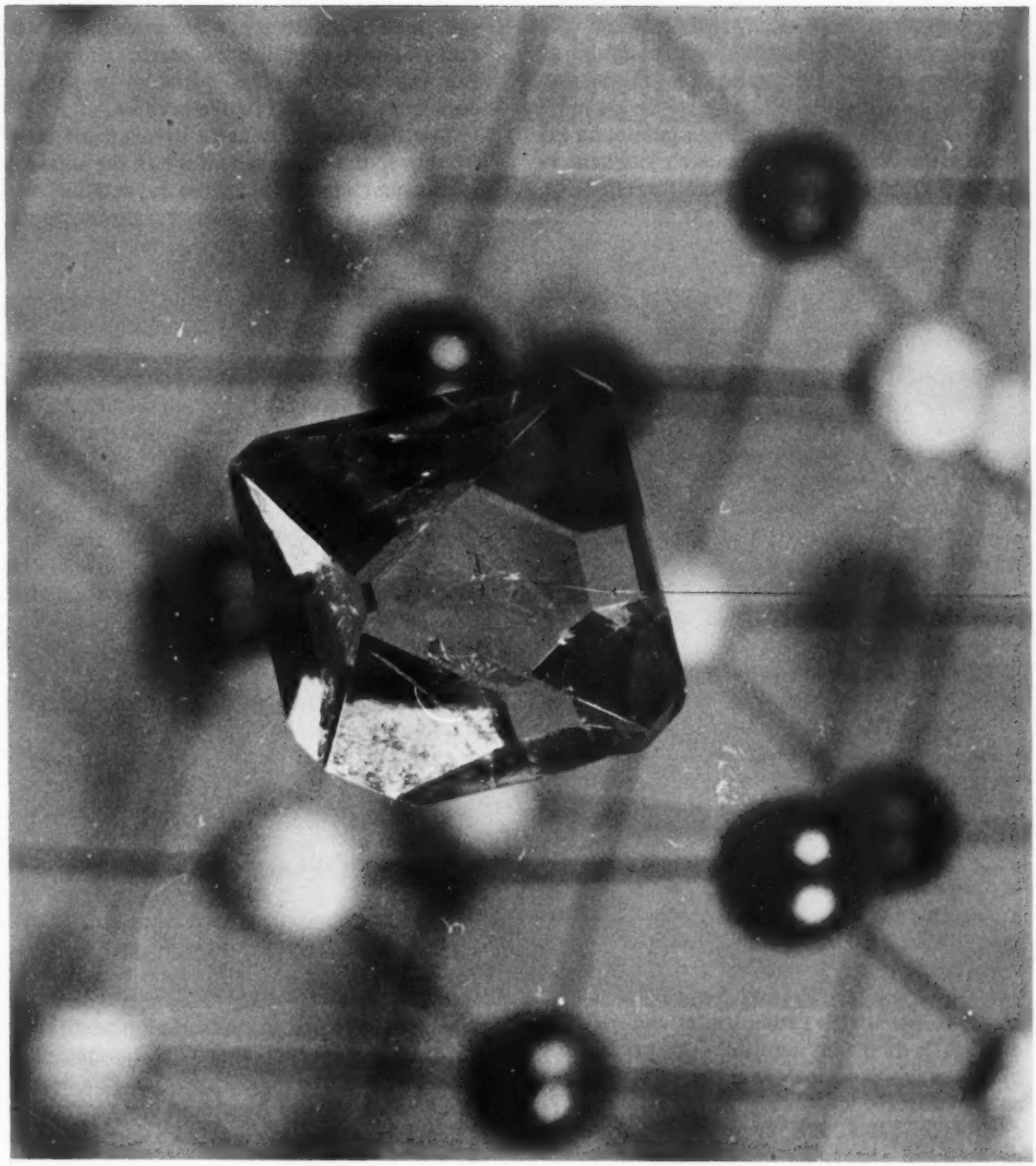


Photo # 1 shows a single crystal of material superimposed on a lattice model background.

understanding. These relationships were uncovered only after the detailed analysis of a massive body of experimental data on more than 100 solids.

The results of Plendl's study have been brought together for the first time in a 134-page manuscript entitled New Concepts in the Physics of Solids, recently submitted for publication. The essence of the paper is in a series of mathematical formulations which

establishes the relationships that exist among characteristic features of materials. The manuscript brings together discrete parts of Plendl's study which have previously been published in the scientific literature. Within the past year alone, Plendl has published six papers on his research in such journals as Applied Optics (July 1965 and March 1966), the Journal of Applied Physics (August 1965), the Journal of Chemical Physics (October 1965), Physica Status Solidi (December 1965), and the Physical Review (June 1966).

Although Plendl's work gives the physicist a new view of materials in the solid state, this does not necessarily mean that the physicist can now apply Plendl's formulations to the characterization of all kinds of solid materials. The research can best be viewed as a path towards an application goal that is still distant. But it is a goal with high potential reward.

Let us consider this work against the broadest possible background. Its potential usefulness covers the full spectrum of materials--metals, semiconductors, magnetic materials, and dielectrics.

Ideally, the materials scientist would like to have a body of theory from which he could draw to predict the optimum stoichiometry of a material for a particular application. He would like to predict the materials that will give optimum strength-to-weight ratios, that transport and manipulate electrons with optimum efficiency, and that can operate in environmental extremes of temperature and radiation. There is no way--except within gross limits and with occasionally brilliant intuition--to predict the optimum composition of a material for a given use. Materials must be synthesized on a trial-and-error basis, and properties defined by subsequent characterization. Such characterization is a laborious, time-consuming task, relative to the ease of synthesizing a particular material.

With Plendl's study as the basis, it may be possible to predict the properties prior to synthesis, and to tailor materials having known optimum properties. Plendl's study to date has been concerned almost entirely with binary dielectric compounds. It has not yet dealt sufficiently with metallic materials or with complex dielectric compounds. But the work to date provides a point of departure for these future studies.

The 10-year study has a diversity of parts. Of these, the central feature is the infrared vibrational spectrum of the crystalline substance as a whole. This spectrum is the material's fingerprint. The infrared spectrum of any material, however, is not amenable to mathematical analysis. A single term is needed to represent the entire spectrum of the material. In the late 1950s, Plendl introduced the concept of a "centro-frequency," which is defined as the center of gravity of the entire spectrum. This centro-frequency became the basic concept around which the entire study revolves.

In a step-by-step progression of mathematical expressions, Plendl relates the centro-frequency to the material's specific heat, and to the material's elastic (acoustic) spectrum. He shows the interrelation of specific heat to compressibility, and of compressibility to the lattice cohesive energy. His equations demonstrate the key role of harmonic and anharmonic lattice vibration in the material. He shows that there are two types of anharmonicity of the lattice structure which have a very different meaning in the atomic structure, and that these two types have a pivotal function in the character of a material. Lattice anharmonicity, for example, is related to the repulsive forces between atoms, and can be used to predict the change of compressibility of the solid with pressure. The relationships have led to methods for predicting the hardness (abrasiveness) of the material, a quality that previously could not be determined in advance of synthesis and testing.

The formulations also make it possible to predict the valences, bond strengths, and the nature of the bonding between atoms in the lattice structure. Last and more general, the study has shed light on, but has not yet fully illuminated, the forces that hold matter together in the solid state. For such illumination, new underlying theories must be postulated. The relationships established by Plendl may provide the key to such theories. ★

PROFILES

Mrs. Rita C. Sagalyn (left) and Dr. Michael Smiddy (right), both physicists in the Upper Atmosphere Physics Laboratory, AFCRL, have collaborated on the design of the "Satellite Attitude-Sensing System Based on Positive-Ion Detection," described in this issue of the Review.

Mrs. Sagalyn received a B.S. in Physics from the University of Michigan in 1948, and an M.A. in Physics from Radcliffe College in 1950. She has been with AFCRL since that time. From 1950 to 1958 she was engaged in an investigation of electrical phenomena in the troposphere, and received the Guenter Loeser Award in 1958 for her work in the lower atmosphere. Since 1959 she has been studying the electrical properties of the upper atmosphere, and the interplanetary gas. Mrs. Sagalyn has published several papers on the results of her research.

Dr. Smiddy received a County Scholarship in Physics and Applied Mathematics to Durham University (England), where he took his B.Sc. in Honours Physics. After serving for two years as a lieutenant in the R.E.M.E. Corps of the British Army, he returned to Durham and received his Ph.D. there in 1958. Dr. Smiddy has been with AFCRL since that time. Presently, he is working on direct probe measurements of electric field and positive-ion density in aerospace.

Captain Howard E. Bethel is assigned to the Hypersonic Research Laboratory, ARL. He has recently completed a detailed study of the solution of the laminar boundary-layer equations with the Galerkin-Kantorovich-Dorodnitsyn method, and is continuing his research on computational methods in boundary-layer theory. His article, "On the GKD method for the Laminar Boundary-Layer Equations," appears in the OAR Research Review this month. Captain Bethel received a B.S. in Aeronautical Engineering, with distinction, from Purdue University in June 1961. He was commissioned in the Regular Air Force at the same time, and stationed at Purdue. While there, he received an M.S. in Engineering in June 1963, and satisfied the Ph.D. residence requirements. After coming to ARL, he completed his dissertation in absentia, and was awarded the Ph.D. degree in June 1966.

Dr. Johannes N. Plendl is a physicist with the Solid State Sciences Laboratory, AFCRL. He obtained his B.S., M.S., and Ph.D. degrees from the Munich Institute of Technology (Germany) where, from 1919 to 1925, he majored in electrical engineering and physics. In Germany, from 1925 to 1946, he held many important Government positions in the field of R&D in radio, UHF, and microwave electronics. Dr. Plendl has made major contributions to the theories of UHF-, surface-, and ionospheric wave propagation, and was the first to propose the name, "ionosphere," in 1930. He came to the United States in 1947, joined AFCRL in 1948, and became a U.S. citizen in 1956. The article, "Properties of Materials in Solid-State Form," in this issue of the Review, discusses some aspects of his recent work.

Lt Col William W. McKenna, author of the article, "An Investigation of the Behavior of a Detonation Wave in a Flowing Combustible Mixture" appearing in this issue of the Review, was awarded the Ph.D. in Aeronautical and Astronautical Engineering by the Ohio State University in June 1966. After four years as Associate Professor of Mechanical Engineering at the Air Force Institute of Technology, Air University, Wright-Patterson Air Force Base, Ohio, he was recently reassigned to Headquarters, Air Force Systems Command, Andrews Air Force Base, Maryland, as an R&D staff officer. Col McKenna received his B.S. from Pennsylvania State University in 1943, and his M.S. in Aeronautics (1953) and Engineering degree in Aeronautics and Astronautics (1962), both from M.I.T. The research he describes in his article was performed at AFIT under the auspices of ARL's Fluid Dynamics Facilities Research Laboratory.

Mr. Norman J. Macdonald has been a research physicist with the Meteorology Laboratory of AFCRL since 1961, concentrating on the fundamental problem of fluid motions on rotating, differentially heated spherical systems. He attended the California Institute of Technology, from which he received the B.S. (1946), and the M.S. in Meteorology (1947). Before coming to AFCRL, he was Senior Scientist with the AVCO Corporation. A member of the American Meteorological Society and the American Association for the Advancement of Science, Mr. Macdonald is the author of some 16 papers on meteorological and geophysical subjects. An article appearing in this issue of the Review, "Hypothesis by a Martian Astronomer," briefly discusses Mr. Macdonald's study of the movements of closed cyclonic and anticyclonic pressure centers.

Mr. Owen W. Williams (right), Chief of AFCRL's Terrestrial Sciences Laboratory, is being congratulated by Dr. A. Marussi, Chairman of the Italian Geodetic Commission, after delivering a paper on AFCRL's geodesy program at a seminar on Mathematical Geodesy held last year in Turin, Italy. He writes on "Anna and Progeny" in this issue of the Review. Mr. Williams attended Kalamazoo College in Kalamazoo, Michigan, and Franklin and Marshall College in Lancaster, Pa., receiving his A.B. with honors from the former in 1948. He also attended graduate school at The George Washington University from 1948-1950, and has done graduate work in Geophysics and Management at universities in the Boston area. After naval service during World War II, Mr. Williams served as a geodesist with the Army Map Service from 1948 to 1955. From 1955 to 1957, he was successively Assistant Chief and Chief of the Geoscience Branch, Aeronautical Chart and Information Center. He has been with AFCRL since 1957. Mr. Williams is a member of several professional societies.